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WATER VAPOUR CONTENT AND ITS EFFECT ON CABA REGULATOR FREEZE-UP

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ABSTRACT

During the winter months the Canadian Forces (CF) have experienced problems with high water content levels in divers' compressed breathing gases. One problem investigated was the validity of the standard used to specify water content levels. The standard suggests that water is a contaminant in the compressed gas because it might cause freezing of the breathing apparatus regulators. Present thinking disagrees with this suggestion; consequently, an experiment was performed in which 4 diving regulators used by the Canadian Forces were tested in -1.0 to 0.0°C salt water. Two conditions were tested. The first used compressed air saturated with moisture at 3000 psig. The second used air at 3000 psig with no more than 5 millilitres per cubic metre (mL/m^3) by volume water content. The protocol created freeze-up conditions by activating the second stage purge button for 5 s, stopping for 5 s and then repeating this cycle until 1500 psig remained in the supply cylinder. Only one of the regulators did not free-flow in either condition; however, no free-flows were attributed to ice. Instead, material performance under cold conditions was blamed. Therefore, it was recommended that the CF standard be revised to remove water vapour as a cause of compressed air breathing apparatus regulator freeze-up. The recommended maximum level for moisture content in compressed air breathing apparatus air supplies was 50 mL/m^3 by volume based on the standards used by other NATO forces. Calculations revealed that at this level the gas would contain little water to cause corrosion; however, it was considered prudent to recommend an analysis of the possibility of corrosion in compressed gas distribution and storage facilities.

1. INTRODUCTION

The Canadian Forces (CF) uses the nomograph, Figure 1, found in their standard for purity of compressed breathing air and gases for divers [1] to control water vapour content and determine the minimum ambient operating temperature for a supply of compressed gas. Once the water content of a gas supply is determined, the minimum ambient temperature (point C on Figure 1) is obtained by joining the measured water content and the maximum supply pressure (line AB). This method has resulted in a large number of gas supplies exceeding the allowable water content for winter operation. The nomograph came under suspicion when the water content specifications of other countries were examined. For example, England uses a limit of 50 millilitres per cubic metre (mL/m^3) by volume. The line joining 50 mL/m^3 by volume and 3000 psig (line DB) intersects the temperature scale at about 16°C. The Royal Navy operates in water temperatures below 10°C without freeze-up problems. Therefore, it became obvious that the nomograph method was faulty. As part of an evaluation of the CF in-service compressed air breathing apparatus (CABA) (Chief of Research and Development Control Number DMEE 048), the Director of Marine and Electrical Engineering (DMEE) tasked the Experimental Diving Unit (EDU) of the Defence and Civil Institute of Environmental Medicine (DCIEM) to investigate the problems with the nomograph. The work presented here was completed to determine the suitability of the present water content specification and the use of the nomograph.

The CF standard [1] considers moisture a gas contaminant because it may cause corrosion or result in regulator freeze-up. Freeze-up is a term used to describe a CABA regulator malfunction most often characterized by a violent free-flow of gas. The free-flow makes breathing difficult and, if the malfunction causes buoyancy-control vest or dry suit inflation valves to open, then uncontrolled ascent and the danger of arterial gas embolism occurs. The alternate freeze-up condition where the CABA valve closes is an obvious danger; however, its rate of occurrence in CF regulators is very low.

A number of possible freeze-up mechanisms exist including the precipitation of ice out of a compressed gas supply and subsequent fouling of regulator internal components. In 1973 Fullerton [2] hypothesized that moisture in the supply gas could cause freeze-up, but no experiments were performed to test the hypothesis. The statement was made on the basis of theoretical ice formation in no-flow systems.

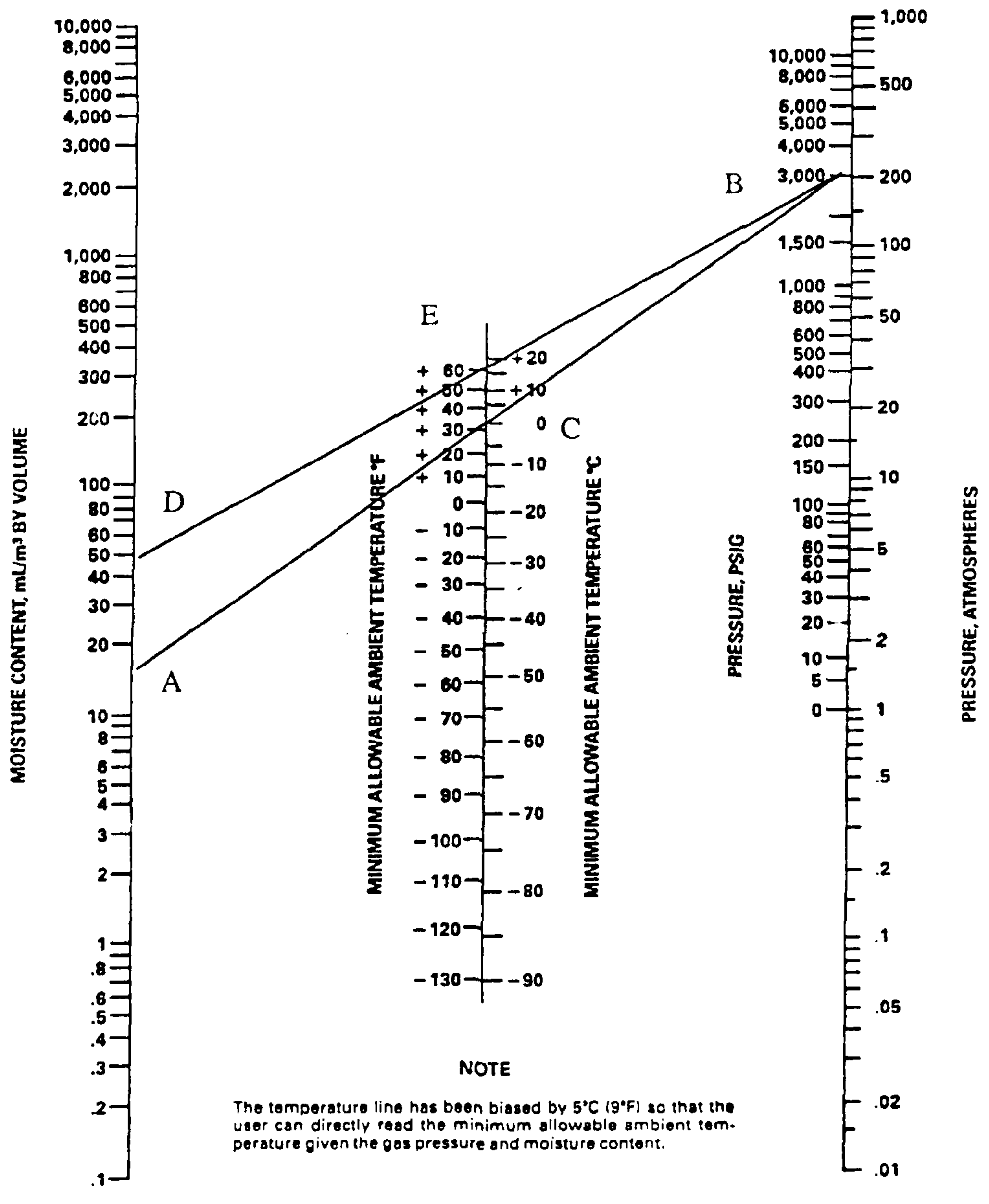

Figure 1. Nomograph for minimum allowable ambient temperature.

Burgess [3] described the presence of water in breathing gas as a potential for freeze-up. He recommended that, to prevent ice formation while operating in waters near 0°C, compressed air should contain no more than 17 ml/m^3 by volume. At these concentrations, the gas would have a dew-point of about -5°C when compressed to 3000 psig, which allows for some adiabatic cooling in the regulator. This concentration corresponds to the limit now used in the CFTO gas purity standard [1] when the ambient operating temperature is 0°C. Burgess recommended this concentration on the assumption that ice could form inside the CABA regulator.

However, the present feeling is that, in the first stage of a CABA regulator, gas velocities are very high and consequently the gas molecules have high kinetic energy. The high energy levels suggest that ice formation may be unlikely. In discussions with representatives of the CABA manufacturers Scubapro and AGA/Interspiro, they claimed that freezing of water in compressed gas would not occur in the first stage of a CABA regulator. However, neither of these manufacturers provided any documented evidence, either theoretical or experimental, that supported their claims. An informal experiment, performed by CF Clearance Divers, involved partially filling a gas cylinder with water, charging the cylinder with air to 3000 psig, connecting a CABA regulator, and then purging and breathing from the regulator in an attempt to cause a freeze-up. Although the experiment was performed in near freezing conditions, the divers indicated that no freeze-ups occurred.

Consequently, a more formal experiment was performed to test whether or not extreme conditions would cause ice to form inside the first stage regulator of in-service CF CABA. The experiment reproduced worst case conditions for first stage freeze-up by using compressed gas saturated with water, salt-water immersion temperatures between -1.0 and 0.0°C, and high gas flowrates produced by repeated 5 s actuations of the second stage regulator purge valve.

2. METHODS

Each regulator was tested three times each under a control and an experimental condition. In the control condition the gas cylinders were dried under vacuum. The cylinders were pressurized to 3000 psig with dry gas (no more than 5 ml/m^3 by volume water vapour). In the experimental condition one litre of distilled water was placed in the cylinders. After pressurizing to 3000 psig with dry gas, the cylinders were rolled to ensure good mixing and rapid water vapourization. Nonetheless, water vapour pressure in the cylinder was given at least 3 hours at 20 ± 1°C to reach saturation.

Two Scubapro MK V regulators with Silicone Protected Environmental Caps (S.P.E.C.) and two U.S. Divers Conshelf XIV Supreme regulators were randomly selected from the EDU Clearance Divers supply. (Note: The Supreme designation indicates the first stage regulator is equipped with a U.S. Divers cold water conversion kit, Part No. 1088-50.) An EDU Clearance Diver serviced the regulators by prior to the trials. If required, the Scubapro S.P.E.C. was topped up with silicone grease (Scubapro Environmental Silicone, Part No. 41-035-000) before each test. The Conshelf first stage regulators were equipped with the nylon reinforced diaphragms as opposed to the more flexible cotton reinforced diaphragms [4] and the first stage freeze-up protection caps were filled with silicone oil (U.S. Divers Part No. 1088-55). Two aluminum 80 cubic foot and two steel 90 cubic foot gas cylinders, all rated to 3000 psig, were used. First stage regulators were equipped with intermediate and high pressure gauges.

Tests were conducted in the water tank of the EDU's Unmanned Test Facility (UTF). The salt water in the tank was maintained between -1.0 and 0.0°C.

Each regulator was tested individually. A regulator was connected to a fully charged cylinder and then the cylinder and first stage were submerged in the water tank. The second stage was kept dry. The cylinder was laid horizontally to maximize the internal water surface area but keep the cylinder valve dip tube dry. The intermediate pressure was recorded and the experiment started. The operator held the second stage out of the water and depressed its purge button for five seconds and then released it for five seconds. This purging cycle continued until the cylinder pressure was 1500 psig at -0.5°C. During the test the maximum intermediate pressure, the number of purges, free-flow occurrence, the intermediate pressure upon reaching 1500 psig and the build-up of ice on the regulator were recorded.

3. RESULTS

In the control condition, Table 1, 5 freeze-up events occurred (1 with a Scubapro, 4 with US Divers) while only 2 freeze-ups, both with U.S. Divers, occurred during the experimental trials. Only one regulator, a Scubapro Mk V, did not free-flow in either control or experimental conditions. Both U.S. Divers Conshelf XIV regulators free-flowed to some extent under both conditions. (Note: Data for the third trial with regulators 1s and 1c in the experimental condition were not available.)

The intermediate pressure at the start of the trials was between 145 and 150 psig in all cases except one, i.e., Trial 2 of the experimental condition with regulator 2c started at 135 psig.

The intermediate pressure at the end of the trials was 0 to 15 psig higher than the starting pressure.

In tests in which no freeze-up occurred, the U.S. Divers regulator required 2 to 3 times as many purges as the Scubapro to reach a cylinder pressure of 1500 psig. This means that the gas flow rates during purging were much higher in the Scubapro regulator.

Regulator No.	Trial No.	Intermediate Pressure			No. of Purges	Free-flow	Ice Build-up	Cylinder	Comments
		Start	End	Maximum					
1s	1	146	150	170	11	No	Yes	90 ft^3	
	2	150	160	165	10	No	Yes	80 ft^3	
	3	145	145	205	9	Yes	Yes	80 ft^3	Slight free-flow.
2s	1	145	145	155	13	No	Yes	90 ft^3	
	2	145	160	165	12	No	Yes	80 ft^3	
	3	145	150	170	12	No	Yes	80 ft^3	
1c	1	150	150	180	30	Yes	No	80 ft^3	Slight free-flow.
	2	145	145	180	32	No	No	90 ft^3	
	3	145	140	180	31	Yes	No	80 ft^3	Slight free-flow.
2c	1	150	155	170	24	No	Yes	80 ft^3	
	2	145	150	165	24	Yes	Yes	90 ft^3	Ice on purge button.
	3	150	145	165	18	Yes	Yes	80 ft^3	Strong free-flow; needed to cover mouthpiece with hand to stop flow.

Table 1. Intermediate pressures (psig), free-flow ice formation data from control condition (water vapour content of gas between 3-5 mL/m^3 by volume). Regulators with the suffix "s" were Scubapro Mk V S.P.E.C. and those with "c" were U.S. Divers Conshelf XIV Supremes.

Regulator No.	Trial No.	Intermediate Pressure			No. of Purges	Free-flow	Ice Build-up	Cylinder	Comments
		Start	End	Maximum					
1s	1	145	145	165	10	No	Yes	80 ft^3	
	2	145	160	180	10	No	Yes	80 ft^3	
2s	1	145	140	160	11	No	Yes	80 ft^3	
	2	145	145	150	11	No	Yes	90 ft^3	
	3	145	150	160	12	No	Yes	80 ft^3	
1c	1	145	135	190	29	No	No	80 ft^3	
	2	135	135	180	31	No	No	80 ft^3	
2c	1	150	150	190	9	Yes	Yes	80 ft^3	Very strong free-flow; needed to cover mouth-piece with hand to stop flow.
	2	145	150	180	13	No	Yes	90 ft^3	
	3	150	150	175	16	Yes	Yes	80 ft^3	Very Strong free-flow; needed to cover mouth-piece with hand to stop flow.

Table 2. Intermediate pressures (psig), free-flow ice formation data from experimental condition (gas saturated with water at 0°C). Regulators with the suffix "s" were Scubapro Mk V S.P.E.C. and those with "c" were U.S. Divers Conshelf XIV Supremes. (Note: Scubapro No. 1s and U.S. Divers No. 1c were only tested twice in the experimental condition.

4. DISCUSSION

If high water content causes ice formation in the first stage, then free-flows should have occurred in the majority of the tests done with saturated gas. Instead, only two of ten trials resulted in freeze-ups when saturated gas was used compared to five freeze-ups in twelve trials using dry gas. This evidence does not support the hypothesis that ice formation inside the first stage regulator causes freeze-ups in CABA. Because the regulators are protected from external ice fouling, only one mechanism remains, i.e., changes in regulator material characteristics under extreme cold conditions. Unfortunately, the experimental results were not intended to be used to investigate material problems and therefore cannot be used to support or refute this hypothesis.

However, evidence of the problem being associated with materials comes from Morson [4]. During tests, in 29 ± 1°F salt water, of U.S. Divers Conshelf XIV regulators equipped with nylon reinforced first stage primary diaphragms the intermediate pressures rose to between 187 and 230 psig. The high intermediate pressures were attributed to stiffening of the first stage primary diaphragm. U.S. Divers produced new cotton reinforced diaphragms and when tested under the same conditions the intermediate pressure only rose to between 147 and 157 psig from the initial setting of 145 psig [4]. In the Scubapro regulators, material problems may include stiffening of 'O'-rings and increased viscosity of lubricants. Additionally, spring materials in both regulators can stiffen under cold conditions causing a increase in the spring constant. These changes in the characteristics of the regulator components would reveal themselves as the increase in CABA regulator intermediate pressure exceeds the second stage balance pressure and a free-flow occurs.

Considering that CABA regulator freeze-up can no longer be attributed to water in the compressed gas, the CF standard for moisture content [1] should be reviewed. Remembering that corrosion is another consideration when setting moisture levels, a study to determine the water content of compressed gas that keeps corrosion within safe and acceptable limits should be done. In the interim, a maximum level of 50 mL/m^3 by volume has been proposed. This matches other NATO countries such as England, Germany, and Belgium, that use 50 mL/m^3 by volume as a standard. At 50 mL/m^3 by volume, air compressed to 3000 psig contains very little water to cause corrosion. As an example, consider the air in an 80 cubic foot aluminum cylinder at a pressure of 3000 psig and having a water concentration of 50 mL/m^3 by volume or about 0.6 millilitres of water. Assume the cylinder is then used for diving in water at about 0°C where the saturation concentration is about 25 mL/m^3 by volume [5]. The change in saturation concentration causes approximately 0.3 millilitres of water to condense out of the air. This is a negligible amount — doubtfully enough to cause significant corrosion problems. Therefore, a maximum allowable water level of 50 mL/m^3 by volume would be acceptable for the purity standard.

5. CONCLUSIONS AND RECOMMENDATIONS

As present thinking suggests, water freezing inside the first stage regulator is not a likely occurrence. In summary, the results of this experiment do not support the hypothesis that moisture in compressed gas can cause CABA regulator freeze-up. To further confirm these results, EDU will perform a similar trial with the U.S. Divers SE 2 Supreme (the newest addition to the CF in-service regulators). These tests will be done with cotton reinforced first stage primary diaphragms. Additionally, it was concluded that with a moisture content standard of 50 mL/m^3 by volume there would not be enough water present in the gas to produce corrosion problems. It is recommended that, until further information is found, the CF use a maximum allowable water concentration standard of 50 mL/m^3 by volume for compressed breathing gas. Furthermore, future evaluation of the in-service regulators will concentrate on other aspects of freeze-up including leakage of water into the second stage, operational procedures and conditions, as well as component material performance at low temperatures.

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During the winter months the Canadian Forces (CF) have experienced problems with high water content levels in divers' compressed breathing gases. One problem investigated was the validity of the standard used to specify water content levels. The standard suggests that water is a contaminant in the compressed gas because it might cause freezing of the breathing apparatus regulators. Present thinking disagrees with this suggestion; consequently, an experiment was performed in which 4 diving regulators used by the Canadian Forces were tested in -1.0 to 0.0°C salt water. Two conditions were tested. The first used compressed air saturated with moisture at 3000 psig. The second used air at 3000 psig with no more than 5 millilitres per cubic metre (mL/m^3) by volume water content. The protocol created freeze-up conditions by activating the second stage purge button for 5 s, stopping for 5 s and then repeating this cycle until 1500 psig remained in the supply cylinder. Only one of the regulators did not free-flow in either condition; however, no free-flows were attributed to ice. Instead, material performance under cold conditions was blamed. Therefore, it was recommended that the CF standard be revised to remove water vapour as a cause of compressed air breathing apparatus regulator freeze-up. The recommended maximum level for moisture content in compressed air breathing apparatus air supplies was 50 mL/m^3 by volume based on the standards used by other NATO forces. Calculations revealed that at this level the gas would contain little water to cause corrosion; however, it was considered prudent to recommend an analysis of the possibility of corrosion in compressed gas distribution and storage facilities.

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